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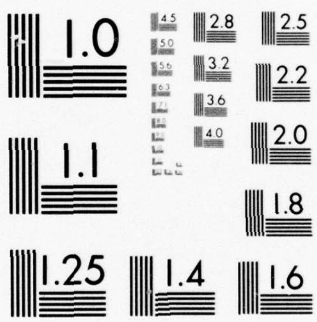

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FINAL TECHNICAL REPORT

OTIS
LASER SCANNER/PHOTODICHROIC
EVALUATION

CONTRACT NO. N00173-76-C-0320

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APRIL 1977

PREPARED FOR
NAVAL RESEARCH LABORATORY
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This report describes the use of an acousto optic laser scanner to perform MTF, photometric sensitivity and dynamic range measurements on a photodichroic crystal (KF:L_i). Signal information was recorded onto the crystal, the spectrum of the recorded signals were obtained, and the signal was recovered by rescanning with an unmodulated laser beam. A resolution of 65 l/mm at an MTF = 50% was measured for the KF crystal. On readout the resolution was 35 l/mm at MTF = 50%. The sensitivity was

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about 3 mj/cm^2 to record onto the crystal with λ = 514.5 nm; decay sensitivity at λ = 488 nm was about 5 times less sensitive than at λ = 514.5 nm. Dynamic range of about 33 dB was measured.

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FOREWORD

This report was prepared by the Electro-Optics Department of the Electronic Systems Division of the Harris Corporation, Melbourne, Florida, under Contract No. N00173-76-C-0320 with the Naval Research Laboratory, Washington, D.C. This effort was monitored by Mr. E. Stevens of NRL.

The program manager was M.O. Greer, who reports to A. Vander Lugt, Director of the Electro-Optics Department. The major contributors to the program were R.G. Hayes and M.O. Greer.

SUMMARY

The primary purpose of this effort was to measure the modulation transfer function (MTF), photometric sensitivity, and the dynamic range of the KF photodichroic crystal, using the OTIS laser scanner as the record/readout system. The OTIS laser scanner uses acousto-optic devices to rapidly scan a focused laser beam across the KF crystal; where the signal information was stored by modulating the laser beam as it was scanned across the crystal.

The results of these experiments indicate that the acousto-optic laser scanner could record 100 MHz (74 lp/mm) signals onto the KF photodichroic crystal with a MTF of about 40 percent. However, due to the limited laser power and low optical efficiency, a minimum of 160 overlapping scans were required to record a signal onto the crystal. To record an average signal (3 mj/cm^2) on the KF crystal with a single scan would require at least a 20 percent efficient optical system and about 3.75 watts of laser power at $\lambda = 514.5$ nm. The OTIS scanner using the KF photodichroic crystal achieved the following performance:

RESOLUTION

RECORD = 65 lp/mm at 50% MTF (for KF crystals)

READOUT = 35 lp/mm at 50% MTF (using PMT)

SENSITIVITY

RECORD = 3 mj/cm^2 (average signal)

READOUT DECAY = 3 dB—4.2 mj/cm^2 at $\lambda = 514.5$ nm

READOUT DECAY = 3 dB—25 mj/cm^2 at $\lambda = 488$ nm

DYNAMIC RANGE

DYNAMIC RANGE = 33 dB (Fourier plane)

= 20 dB (signal readout)

Our conclusion based on this study was that a carefully designed acousto-optic laser scanner system would be required, where the optical efficiency was at least 20 percent. The system would require at least 3.75 watts of laser power to record onto the photodichroic crystal. On readout, if the same scanning spot size was used to recover the signal as the spot size used to record the signal, then a 3 dB decrease in the MTF of the recovered signal can be expected. This would cause the recovered signal to have about 1/2 the frequency content of the signals recorded. The dynamic range appeared to be limited by the equipment used (PMT, polarizers, etc.) and not by the dynamic range of the KF crystal.

SECTION 1.0

INTRODUCTION

1.0 INTRODUCTION

Expanding requirements demand increasingly faster data to be stored and/or displayed in a timely fashion for interpretation and processing. Laser scanning techniques, coupled with the KF photodichroic crystal as a temporary optical signal buffer, offers the capability for accomplishing these tasks.

The laser scanning system utilizes two acousto-optic devices to rapidly scan a focus laser beam across the KF photodichroic crystal. As the laser beam was scanned, the intensity of the beam was simultaneously modulated to record signal information onto the KF photodichroic crystal. (The KF photodichroic crystal was supplied by NRL, Washington, D.C.). An optical Fourier transform was performed to provide frequency information of the signals stored on the crystal. The signals were also recovered from the crystal by scanning with an unmodulated laser beam; the light transmitted by the crystal between two cross polarizers was detected with a photomultiplier tube.

This report describes the experimental results of measuring several parameters of the scanner/KF photodichroic crystal combination to determine the feasibility of using this technology in the Optical Transform Intercept System (OTIS). Section 2.0 of this report describes the scanner system, while Section 3.0 describes the experiments performed using the scanner/photodichroic crystal. In Section 3.0 the modulation transfer function (MTF), photometric sensitivity, and the dynamic range of the system are discussed.

SECTION 2.0

EXPERIMENTAL SYSTEM DESCRIPTION

2.0 EXPERIMENTAL SYSTEM DESCRIPTION

In this section a description of the experimental laser scanner system will be given. The laser scanner was used to record and recover signals stored on the photodichroic crystal. In addition, this section discusses the optical efficiency of the system.

2.1 Scanner System Overview

The system described in this report utilizes acousto-optic devices to rapidly scan a focused laser beam across a recording medium. The intensity of the scanning optical beam was simultaneously modulated; signal information was stored in the recording medium.

The system uses a Bragg-effect, acousto-optic beam deflector (AOBD) working in series with an acoustic traveling wave lens (ATWL) device to produce an extremely fast, high precision laser scanner that uses no moving parts. Figure 2-1 shows a schematic of the experimental system where a detailed view of the fundamental acousto-optic recorder system concept is shown with the photodichroic recording material integrated into the laser scanner system. Figure 2-2 shows a photograph of the experimental breadboard system, that was used to test the photodichroic crystal.

A modulated laser beam was projected through the beam-forming objects, where it was appropriately shaped to match the rectangular aperture of the acousto-optic beam deflector (AOBD). From the AOBD, the light beam was projected through the scanner optical system where it was brought to focus within the acceptable aperture of the acoustic traveling wave lens (ATWL). Hence, as the appropriate drive signal was fed to the AOBD, the output focused beam from the AOBD was scanned across the ATWL cell. The rate of the RF chirp driving the AOBD was fixed at the value required to achieve tracking of ATWL by the beam from the AOBD. As the beam passed through the ATWL, it was further focused to a smaller spot depending on the power of the acoustic lens.

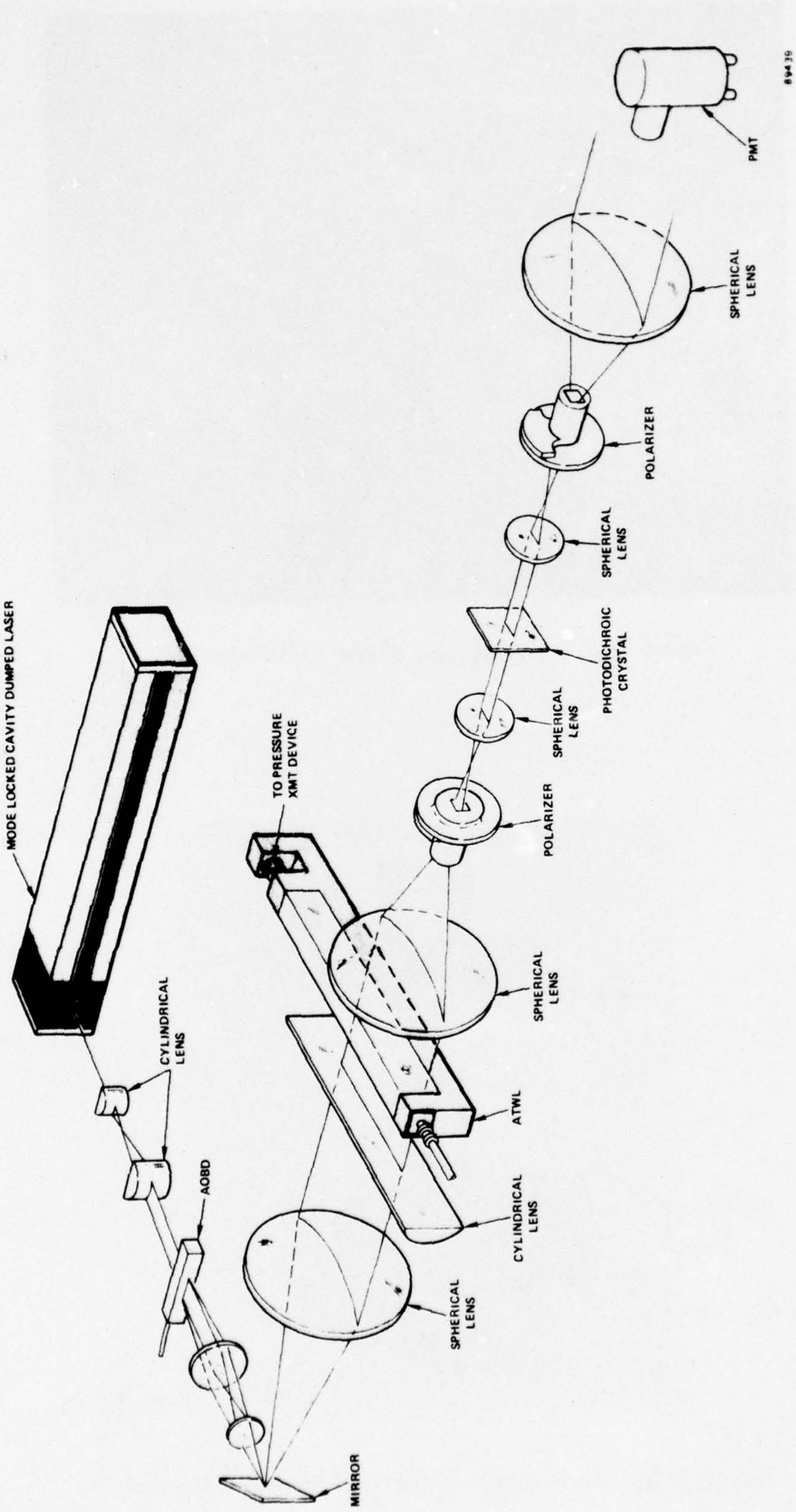

Figure 2-1. OTIS Scanner Breadboard System

Figure 2-2. Photograph of the OTIS Scanner

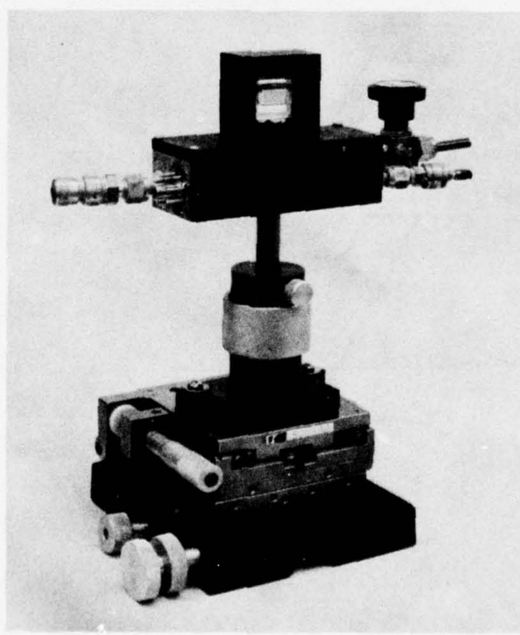

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Figure 2-3. Photograph of the Photodichroic Crystal

A pair of spherical lenses was used to image the ATWL onto the photodichroic recording material at a reduction ratio of 1/3. Hence, the 15 μm spots at the ATWL, become 5 μm spots at the photodichroic crystal plane. A polarizer was placed between the two imaging lenses; its polarization axis was parallel to that of the laser (i.e., vertical). The readout optics consist of a pair of spherical imaging lenses, with a polarizer in between. The second polarizer was crossed with respect to the first. In the output plane, a photomultiplier tube (PMT) was used to collect the light transmitted by the KF crystal in the readout mode. A single line was recorded at 100 MHz signal rate and was read out with the PMT.

A dichroic sheet polarizer is placed in front of the KF crystal during the recording process; the sheet polarizer rotates the polarization 45° with respect to the first polarizer. The sheet polarizer is removed during the readout process.

A more detailed description of the components of the OTIS laser scanner is given in a Naval Research Laboratories Technical Report No. N00173-76-C-0158.

A photograph of the device that holds the photodichroic crystal in the optical system is shown in Figure 2-3. The device was used to cool the crystal down to -60° C, and to protect the crystal from the humid atmosphere, since the KF crystal is hydroscopic. This device and the crystals were supplied to Harris ESD by the Naval Research Laboratories in Washington.

2.2 System Efficiency

A measure of the optical efficiency was made on the system. The optical efficiency is defined as the percent of the incident laser illumination that passes through the system and arrives at the recording plane. The overall optical efficiency of this experimental breadboard system in the recording mode was only 2.4 percent. The optical efficiency measurements were made at individual components and the results are shown in Table 2-1. Note that the least efficient element was the dichroic sheet polarizer, having only 31 percent efficiency. This element could be greatly improved by using an electro-optic modulator as a polarization rotator. The

electro-optic modulator would replace the first polarizer and could be electrically controlled to automatically switch from record to readout polarization. If all the lenses and surfaces had antireflection coatings with transmission coefficients of at least 0.92, then the overall efficiency of the system could be increased by nearly an order of magnitude to approximately 20 percent.

Table 2-1. System Optical Efficiency Measurements

Element	Element Efficiency	System Efficiency
1) Laser	---	100%
2) Scanner	14%	14%
(Lenses and Mirrors)	(41%)	
(AOBD)	(45%)	
(ATWL)	(76.3%)	
3) Spherical Imaging Lenses		
9" Baltar	80%	11%
4" Baltar	78%	9%
Polarizer	87%	8%
Sheet Polarizer	31%	2.4%
Overall Efficiency		2.4%

SECTION 3.0

SYSTEM EXPERIMENTS USING PHOTODICHROIC CRYSTAL

3.0 SYSTEM EXPERIMENTS USING PHOTODICHROIC CRYSTAL

In this section we discuss the experiments performed using the laser scanner/KF photodichroic crystal to determine the feasibility of using this technology in the Optical Transform Intercept System (OTIS). Several experiments were performed to measure the modulation transfer function (MTF) of the crystal and the OTIS scanner, in both the record/readout modes. Experiments were performed with some nanosecond pulses to measure the photometric sensitivity of the KF crystal and will be discussed in the second part of this section. A measure of the dynamic range is also discussed in this section.

3.1 MTF Measurements

The MTF of the OTIS scanner system using the photodichroic crystal as the recording medium will be discussed in this section. The MTF of the OTIS scanner was influenced by the response of the recording material and by the signal recovery technique. Measurement of the MTF of the system will be discussed below where two basic techniques are employed. One technique for measuring the MTF was to use a microdensitometer to scan a photographic recording of the signal reconstructed from the photodichroic storage crystal. The other technique, was to use a photomultiplier tube to electronically reconstruct the signals recorded on the photodichroic crystal.

3.1.1 Signals Reconstructed Onto Film

The MTF of the OTIS scanner was measured by scanning with a microdensitometer, the photographic recording of the signals reconstructed from the crystal. The OTIS scanner employed a photodichroic crystal as the temporary optical signal storage. The photodichroic crystals are supplied by the Naval Research Laboratory, Washington, D.C.

A series of recordings were made on the KF crystal using the laser scanner setup described in Section 2.0. The recordings were made with 100 MHz pulses and a line scan rate of 32 kHz; however, due to insufficient laser power, approximately 3,000 overlapping scans were used to record the data. After the data are recorded on the KF crystal (square wave pattern

with four spots on and four spots off), it is reconstructed from the crystal with a continuous unmodulated laser beam. The signals recorded onto the KF crystal are recovered by imaging the crystal onto a photographic film. Kodak 2496 RAR photographic film was used to record the reconstructed signals at a magnification of approximately six. A series of photographs were taken in the output plane for a corresponding series of signal patterns recorded on the crystal at different exposure levels.

To calibrate the MTF measurements of the photodichroic cyrstal, a series of signals were recorded directly onto the film. This was to measure the MTF of the scanner system without the degradation caused by the crystal. The crystal remained in the system, however, it was not used in the record and readout mode.

The processed film of the direct input signals and the recorded data from the crystal was scanned by a Joyce-Loebl microdensitometer at a 100X linear magnification and a density calibration of 0.13 density unit per centimeter (vertical axis). Figure 3-1 shows the microdensitometer scan across the input square-wave signal recorded directly onto the film at the output plane. The modulation transfer factor for a given spatial frequency is calculated by

$$MT = \frac{10^{\Delta D} - 1}{10^{\Delta D} + 1} \tag{1}$$

where ΔD is the difference in the maximum and the minimum density as shown on the microdensitometer plots. The modulation transfer factor for the input signal recorded directly onto the film at the output plan was measured to be 80 percent (nominal).

Figure 3-2 shows a microdensitometer scan of a photograph of a line of data recorded on the photodichroic crystal. The modulation of a 12 MHz square wave and 100 MHz signal is 99 percent and 40 percent, respectively. The spatial frequency of the 12 MHz and 100 MHz signals recorded at the crystal plane was 9.2 line pairs per millimeter (lp/mm) and 74 lp/mm, respectively.

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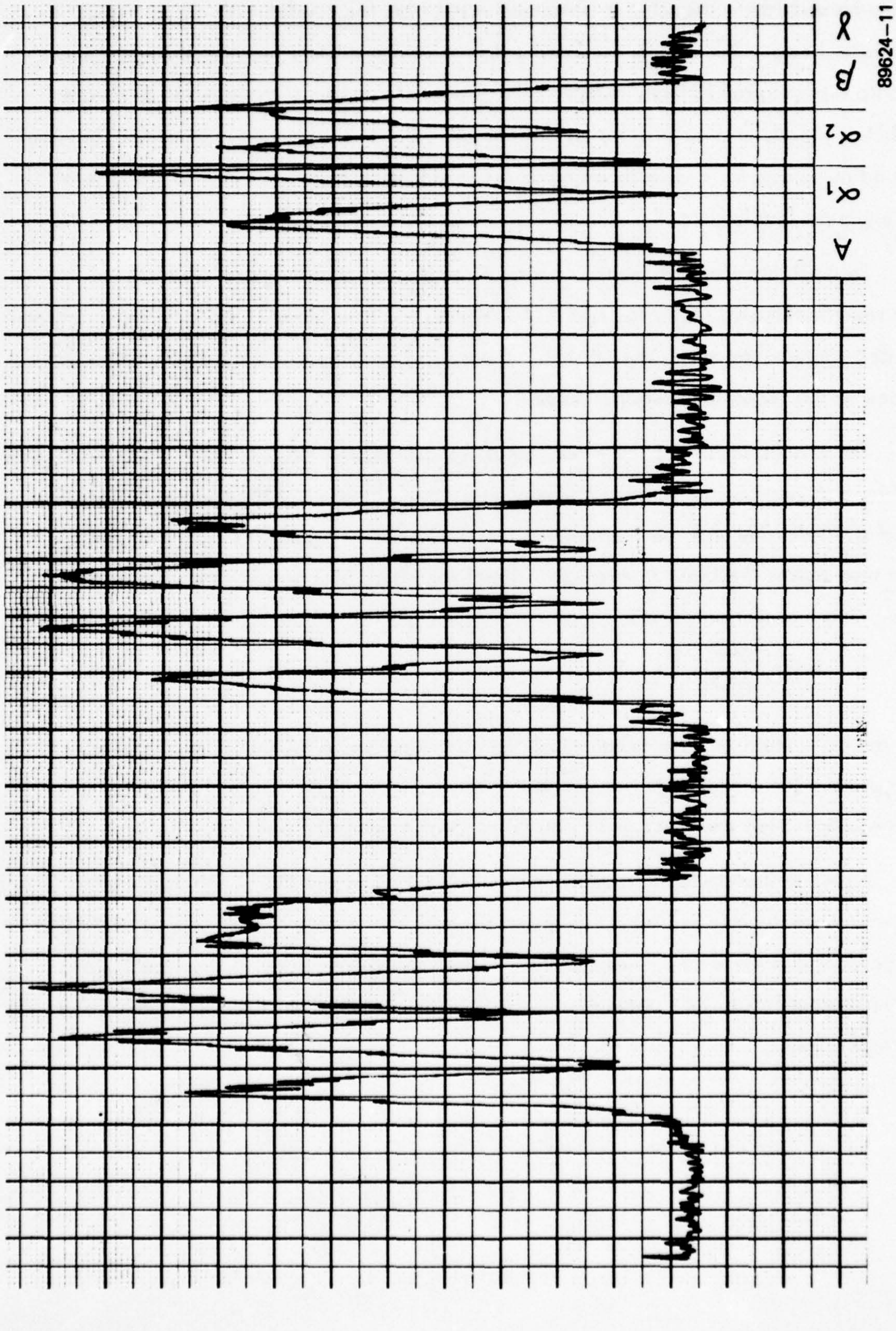


Figure 3-1. Microdensitometer Scan Across the Input

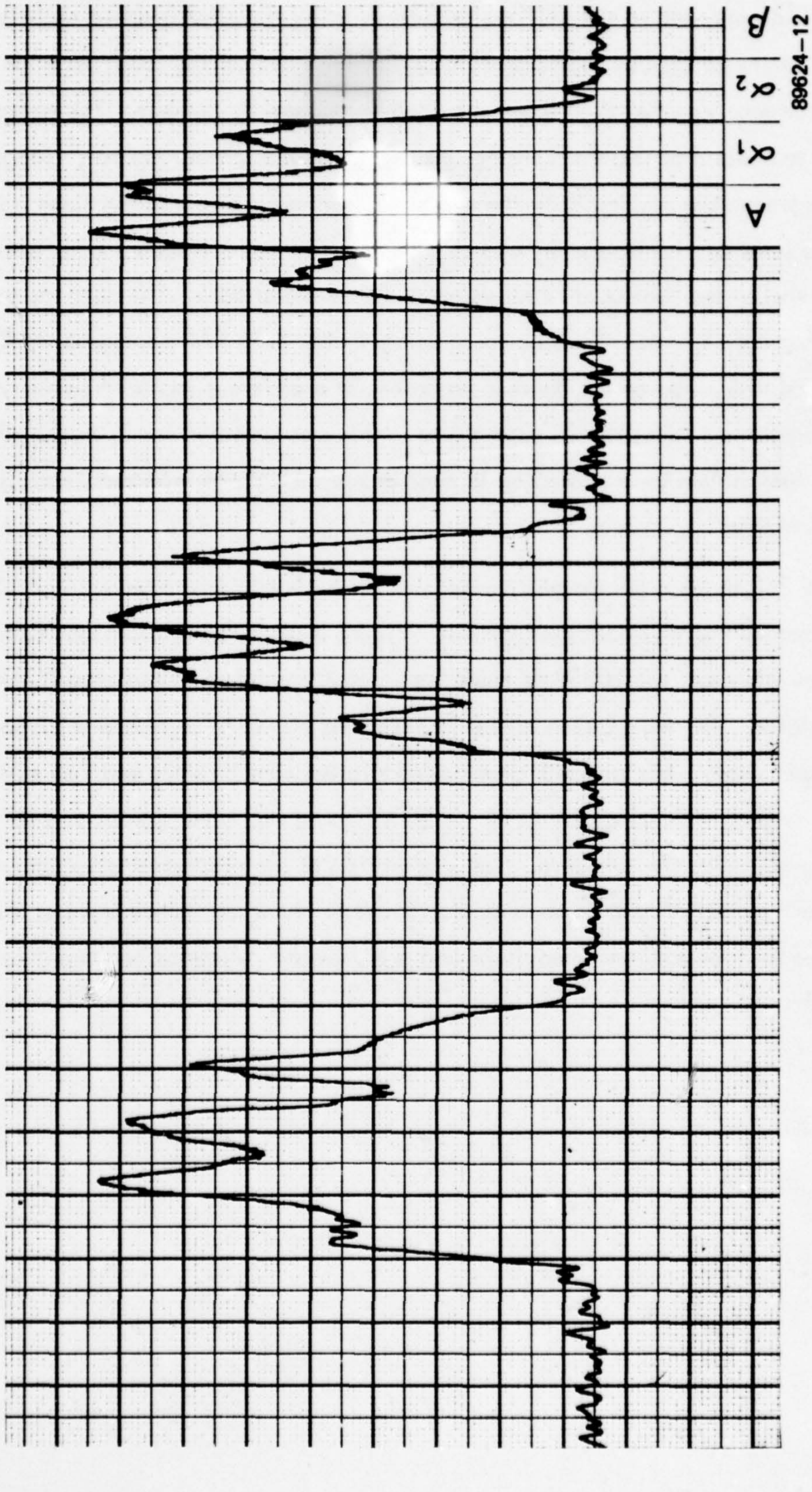
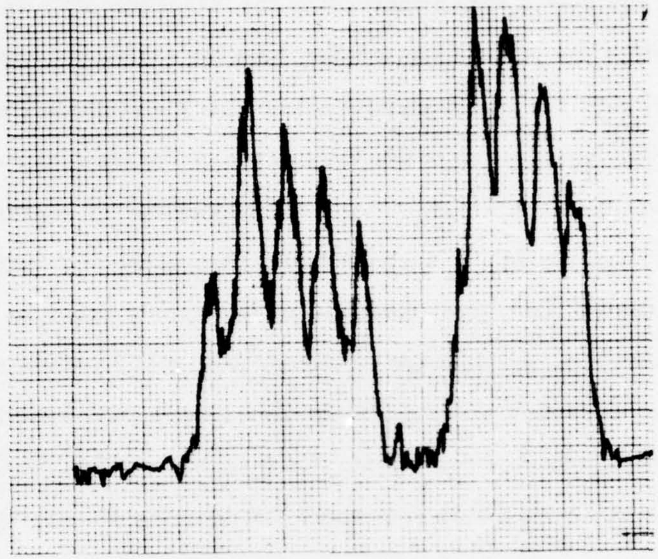


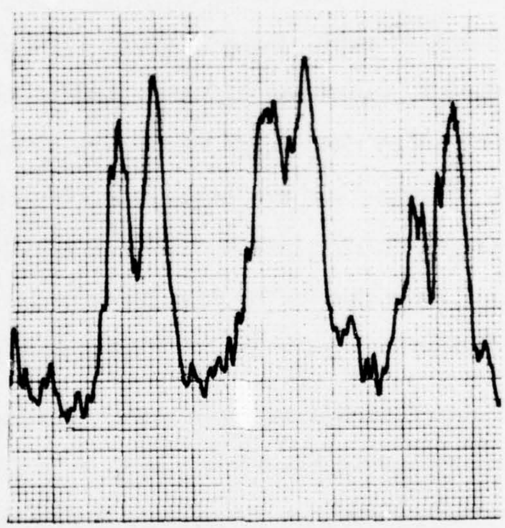
Figure 3-2. Microdensitometer Scan of Data Recorded on the Photodichroic Crystal

A second approach to the MTF measurements using the photographic technique will be described below where an acousto-optic modulator was used to turn the laser beam on and off at amplitudes and frequencies other than those provided by the cavity dumper. The acousto-optic modulator was used to make a series of recordings on the KF photodichroic crystal. The photodichroic crystal was translated vertically in the system and between five and ten lines were recorded on the crystal at the same spatial frequency and exposure levels. A collimated laser beam approxi-amately the size of the crystal was used to reconstruct the recorded data. The data recorded on the crystal was photographed by the 35 mm camera using Kodak 2496 RAR photographic film. The crystal was erased and and prepared for another recording at a different spatial frequency. A second photograph was taken using the 35 mm camera. This was repeated for 3, 6, 12, 25, 50 MHz. The 100 MHz mode lock pulses were presented in most of the recordings; however, some recordings were made with a CW laser.

Figure 3-3 shows a microdensitometer scan of a photograph taken using a 35 mm camera of the signals recorded on the photodichroic cyrstal. Figure 3-3a shows a microdensitometer scan of the 12 MHz square wave and the 100 MHz mode lock pulses recorded on the crystal using the acousto-optic modulator. The modulation of the 12 MHz and 100 MHz signals was 82 percent and 31 percent, respectively. Figure 3-3 shows a modulation of a 25 MHz and 100 MHz signal recorded on the KF crystal. The modulation of the 25 MHz and 100 MHz signals was 76 percent and 40 percent, respectively, for this case. The modulation of the reconstructed signals using the AO modulator was slightly less than the modulation measured when the cavity dumper was used. This indicates that the external modulator had a bandwidth somewhat less than the bandwidth of the cavity dumper.



a. SCAN OF 12 MHz SQUARE-WAVE AND 100 MHz MODE LOCK PULSES



b. SCAN OF 25 MHz SQUARE-WAVE AND 100 MHz MODE LOCK PULSES

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Figure 3-3. Microdensitometer Scan of the Photographs of the Data Recorded on the Photodichroic Crystal

Results of the MTF measurements using the AO modulator, is shown in Figure 3-4. Figure 3-4 shows a graph of the modulation transfer function (MTF) as a function of the spatial frequency. The modulation of the signal reconstructed from the photodichroic crystal is shown as the solid curve drawn. The upper curve is the modulation of the input signal to the KF crystal as seen in the output plane. Note the transfer characteristics of the KF crystal does degrade the signal modulation at all frequencies. This was probably due to the time required to expose the 35 mm film with the reconstructed signal. The MTF of the signals decrease as the signals are being reconstructed. Therefore, the cumulative energy with a 1/2 second exposure causes the reconstructed signals that are recorded on a 35 mm film to have modulation transfer characteristics somewhat less than the modulation of the signals stored on the crystal. Consequently, the MTF of the information stored on the crystal lies somewhere between the two curves shown in Figure 3-4.

The 96.6 MHz signal frequency corresponds to 74 lp/mm at the crystal plane.

3.1.2 Electronically Reconstructed Signals

A second method used to obtain the MTF of the OTIS Scanner, with the photodichroic crystal as the optical storage device, was to use a photomultiplier tube (PMT) to electronically reconstruct the signals recorded on the crystal. The focused laser beam was scanned past the signals recorded on the crystal; at those locations where a spot has been recorded, the transmission of the laser beam through the cross polarizers was increased due to the polarization rotation effect, caused by the crystal. The light transmitted by the cross polarizers was detected by a photomultiplier tube which converts the modulated light signals into modulated electrical signals.

A series of spots were recorded on the crystal, and a signal was then reconstructed by scanning the recorded spots with an unmodulated laser beam. A 56 UVP photomultiplier tube was used to detect the light transmitted by the cross polarizers. The output of the photomultiplier was displayed on an oscilloscope (Tektronix 7904) and a photograph was taken. A 12 MHz square wave and the 100 MHz mode lock pulses were recorded on the KF crystal; Figure 3-5 shows a reconstructed signal displayed on the oscilloscope. Figure 3-5a shows the PMT readout from the KF crystal, where the 12 MHz signals were easily recovered. The MTF of the 12 MHz signal was >80%. However, the 100 MHz signal was not recovered using this technique.

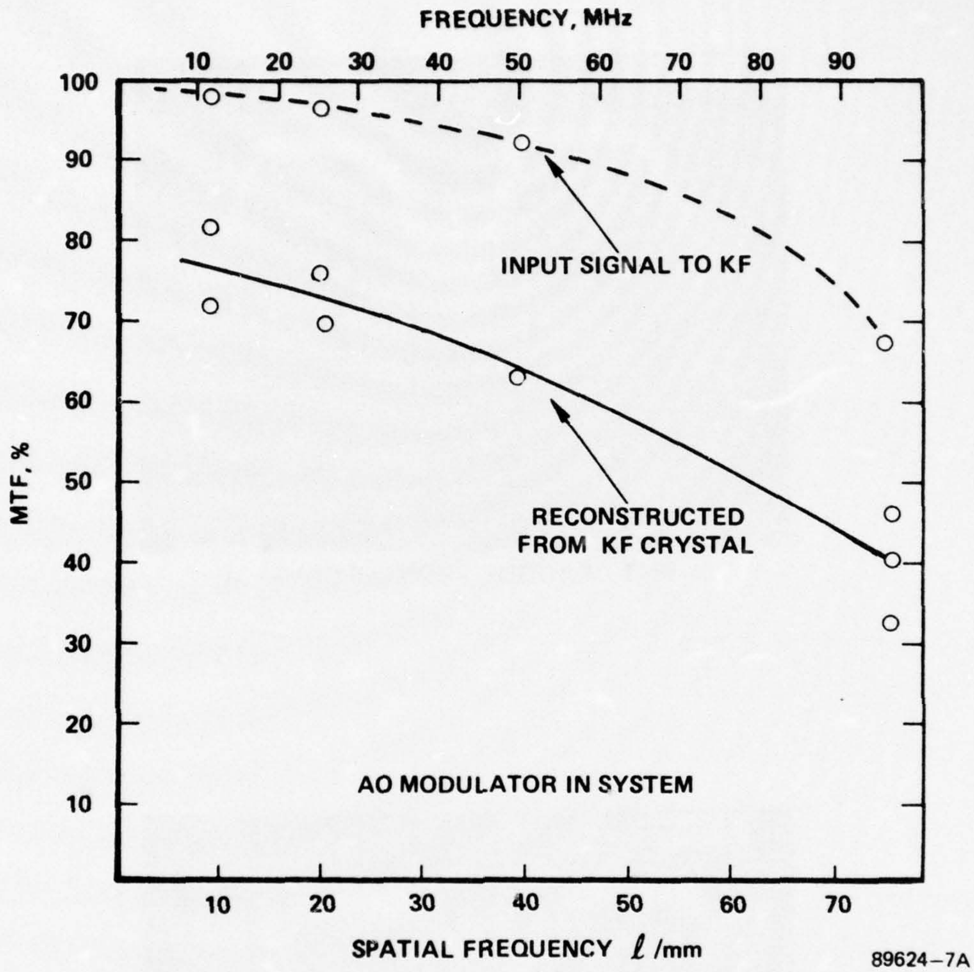
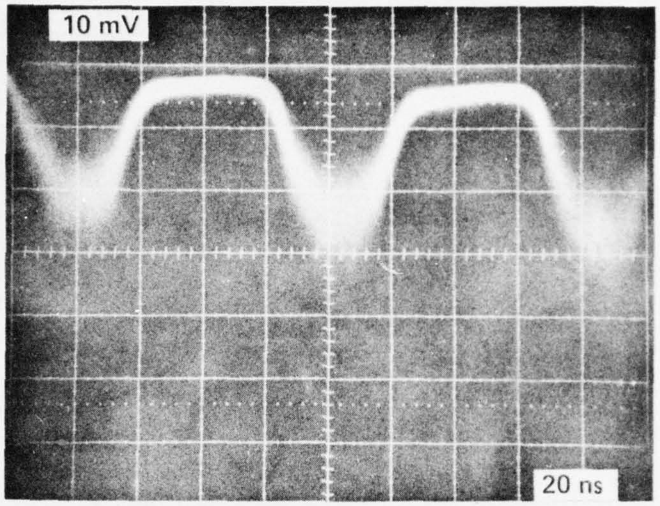
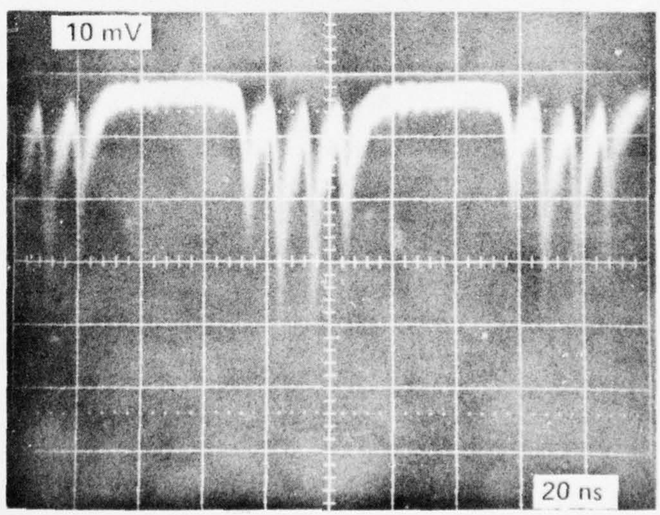


Figure 3-4. MTF Versus the Spatial Frequency

A second photograph was taken of the input signal to the crystal, to determine the response of the photomultiplier tube to the 100 MHz signals. Figure 3-5b shows a photograph of the PMT response to the input signal. Note, that the photomultiplier was capable of responding to the nanosecond pulses from the mode lock cavity-dump laser; however, the 100 MHz signal was not recovered on readout from the crystal. This leaves two possibilities; either the crystal was not capable of recording the 100 MHz (74 lp/mm) pulses or the readout technique has degraded the signals to the point where they cannot be resolved.



a. PMT READOUT FROM KF CRYSTAL



b. PMT RESPONSE TO INPUT SIGNAL

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Figure 3-5. Reconstructed Signals From KF Crystal

From the experimental work performed in Section 3.1.1, we know that the crystal was capable of recording spatial frequencies of 74 lp/mm with an MTF of 40 percent, therefore, the readout technique must be at fault.

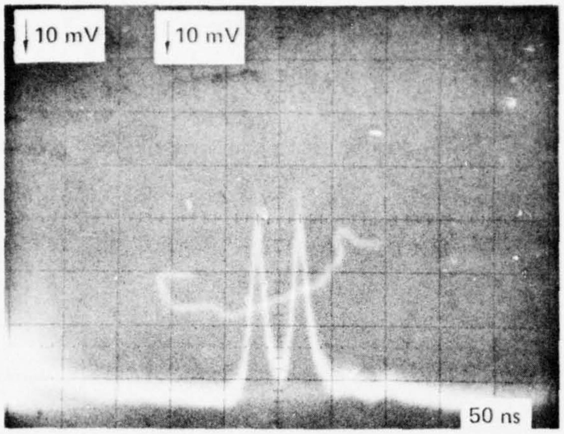
Part of the problem was due to the fact that the readout spot size was the same as the recording spot size; therefore, the convolution of the two spots should decrease the MTF of the reconstructed signals by at least a factor of 2. In fact, we found that the MTF was decreased by more than a factor of 2.

Another experiment was performed to determine the MTF of the scanned reconstructed signals using the photomultiplier tube as the detector. The electronics were adjusted to dump a single spot from the laser at a 3 MHz rate producing a series of widely spaced spots that were recorded onto the KF crystal. On reconstruction of the recorded spots, the output signal from the PMT was power split into two signals, one of which was connected to the first channel of the Tektronix 7904 oscilloscope. The second signal was connected to a box with calibrated delays; the delays range from 0-40 ns. The output of the "delay box" was connected to the second channel of the oscilloscope. The signals from the first and the second channels were electronically added and displayed on the oscilloscope.

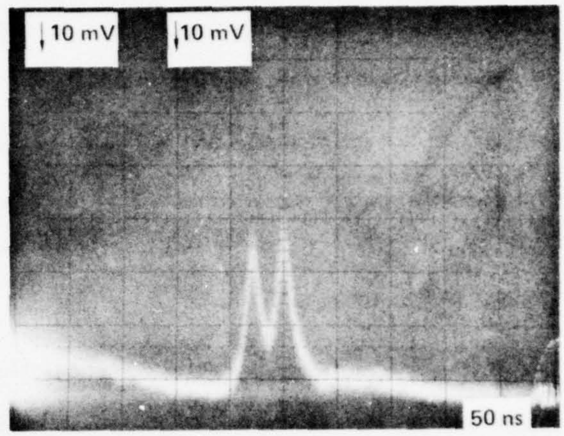
Figure 3-6 shows a series of four photographs where the spot profiles have been delayed by varying amounts. The first photograph shows the two spots separated by a 40 ns delay; the next photograph shows the spot profiles with 30 ns, 20 ns, and 15 ns delays, respectively. The modulation depth is measured between the two spots. The 40 ns delay corresponds to a spatial frequency of 19 lp/mm, where the

$$\text{Spatial Frequency} = \frac{1}{mvt} = \frac{1}{(.41)(3.2\,\mu m/ns)(40\,ns)} = 19\ lp/mm$$

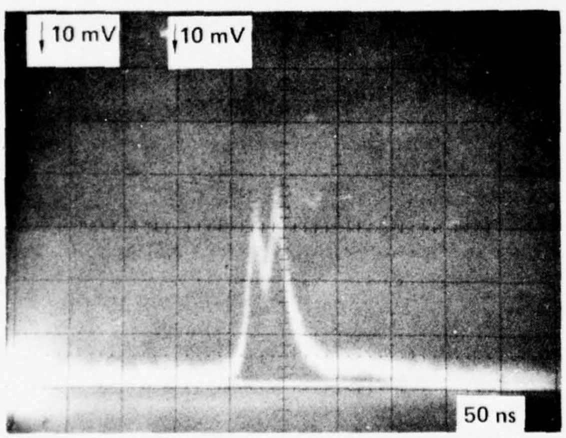
and v was the acoustic velocity of the SF-59 glass used in the ATWL while, m was the magnification from the ATWL to the photodichroic crystal. The modulation displayed by the 40 ns delayed pulses was also the modulation that would be displayed by a 25 MHz signal recorded and reconstructed from the KF crystal.



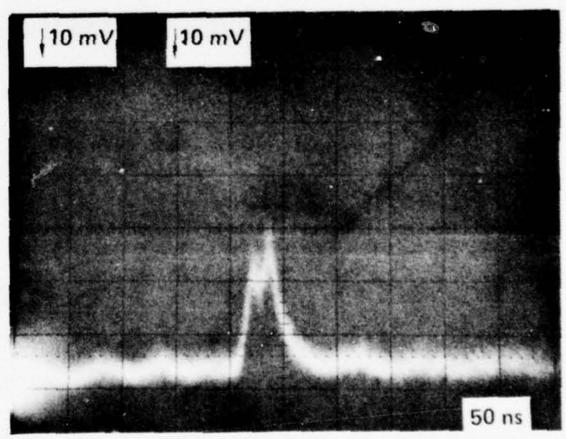
a. SUPERIMPOSED SPOTS
40 ns DELAY AND ADDED



b. SUPERIMPOSED SPOTS
30 ns DELAY AND ADDED



c. SUPERIMPOSED SPOTS
20 ns DELAY AND ADDED



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d. SUPERIMPOSED SPOTS
15 ns DELAY AND ADDED

Figure 3-6. MTF Measurement of Reconstructed Signals Using Delayed Spot Technique

Figure 3-7 shows a graph of the MTF of the reconstructed signal vs the spatial frequency using the PMT with the delayed spot technique. Note that 85 percent modulation was obtained at 20 lp/mm, and approximately 25 percent modulation at 50 lp/mm. The corresponding signal recording and readout frequency is shown at the top of the graph. Note that the 50 lp/mm corresponds to approximately 66 MHz.

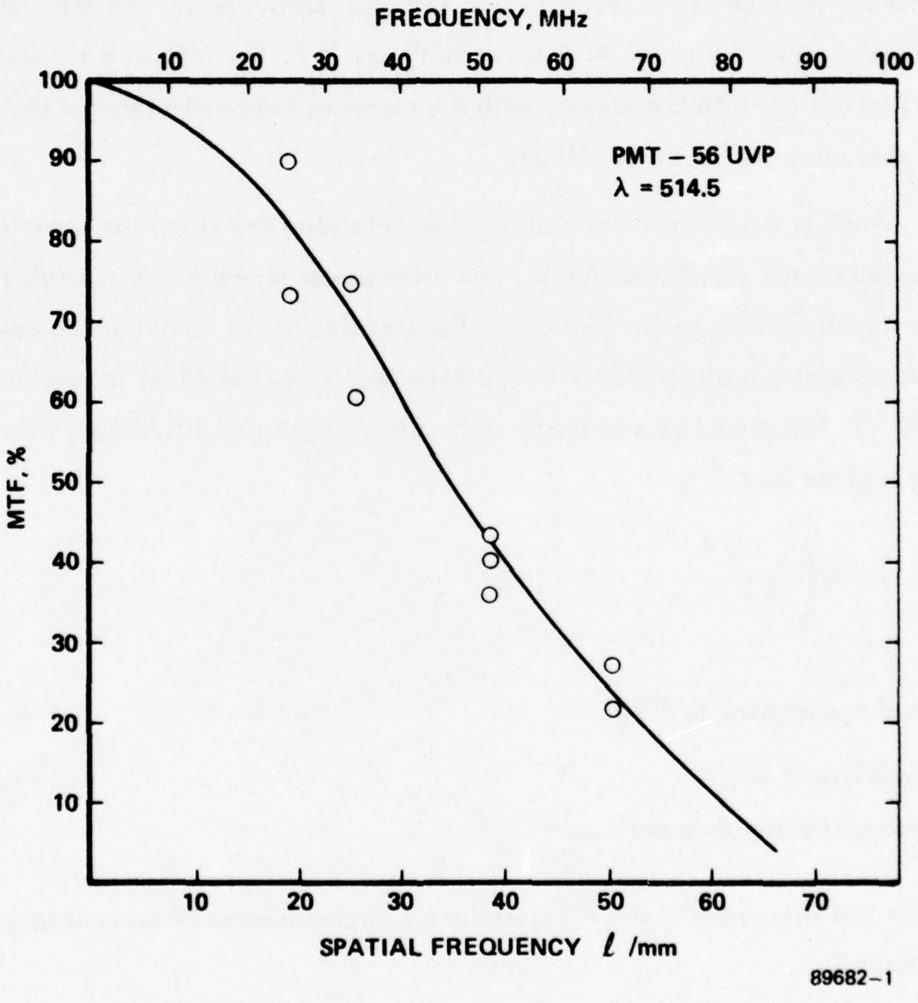


Figure 3-7. MTF Versus Spatial Frequency of Signals Reconstructed Using the PMT, and the Delayed Spot Technique

Comparing the results shown in Figure 3-7 to the MTF measurements shown in Figure 3-4, two things can be noted. First, the high frequency signals are definitely affected by reconstructing the signals with the same spot size. Secondly, the MTF of the low frequency signals was slightly better using the electronic approach because of the short time required to obtain the signals, whereas relatively long exposure times are required to photograph the signals recorded on the KF crystal causing a degradation in the signal modulation recorded on the film. This implies that the modulation of the signals on the crystal is much better than what was shown in Figure 3-4; however, because of the convolution of the recorded spot with the readout beam, the modulation of the recovered signal was limited to the MTF shown in Figure 3-7. The MTF of a KF crystal was 50 percent at 65 lp/mm (80 MHz); however, with the scanning laser beam readout technique, the MTF was 50 percent at 35 lp/mm (47 MHz).

Another experiment was performed to determine the effect the scanning laser beam has on the reconstructed signal modulation. The drive power to the ATWL controls the focusing power of the traveling lens, hence controlling the spot size at the output of the cell. A series of widely spaced spots were recorded with 600 volts applied to the ATWL (normal voltage on the ATWL is 1200 V). This produced a series of spots with diameters slightly larger than normal where the spot size is given by

$$\delta = C\left(\frac{1}{V}\right)^{1/4}$$

where V = voltage applied to ATWL

δ = spot size at ATWL

C = proportionally constant

Therefore, the spots recorded in the KF crystal were approximately 19 percent larger than those normally recorded.

Recovery of the signal was made with a scanning laser beam with 1200 and 600 volts applied to the ATWL. The delayed spot technique was used to determine the modulation of the readout using the two applied voltages. A modulation of 48 percent was obtained using a 1200 volt drive to the ATWL, however with 600 volt drive to the ATWL the modulation was only 38%. This implies that an increase in modulation can be achieved on the readout if a smaller spot (higher voltage) is used to scan the data than the spot used to record the data.

3.2 Sensitivity Measurements

In this section we discuss the measurements made on photometric sensitivity of the KF crystal. The decay sensitivity was measured on readout at two different wavelengths. A measure of the energy required to record on the crystal at 100 MHz rate is given along with an estimate of the size of laser required in an operational system.

3.2.1 Recording Sensitivity

The exposure sensitivity of the photodichroic (KF) crystal was reported to be 3 mj/cm^2 at a wavelength of 514.5 nm. A number of measurements were made using the OTIS scanner with subnanosecond pulses to determine the exposure sensitivity. The exposure sensitivity of the photodichroic crystal can be determined from the following equation:

$$S = \frac{P_{\eta} T}{A} \cdot N$$

where P is the average illumination power from the laser, and η is the system optical efficiency, T is the pixel exposure time, A is the area of the focused spot, and N is the number of overlapping scans. The minimum number of overlapping scans that could be recorded and dichroism detected using a PMT was 160 scans. Therefore, the minimum exposure sensitivity was:

$$S = \frac{(315 \text{ mW})\ (0.24)\ (10^{-9} 5)}{(42 \text{ spots})\ (5 \times 10^{-4})^2 \text{ cm}^2/\text{spot}} \cdot 160 = 0.14 \text{ mj/cm}^2$$

Minimum exposure sensitivity of 0.14 mj/cm^2 using the PMT produces a readout response of about 5 mV and a signal-to-noise ratio of about 2. This exposure sensitivity value was dependent on the extinction ratio of the crossed-polarizers and the sensitivity of the PMT. The minimum exposure sensitivity could be improved with better equipment and signal detection techniques. Using Fourier transform techniques (to be discussed in Paragraph 3.3.2) the minimum exposure sensitivity was about 60 μj/cm^2. However, this sensitivity value was obtained from observing the signal in the Fourier plane, and not from signal recovery.

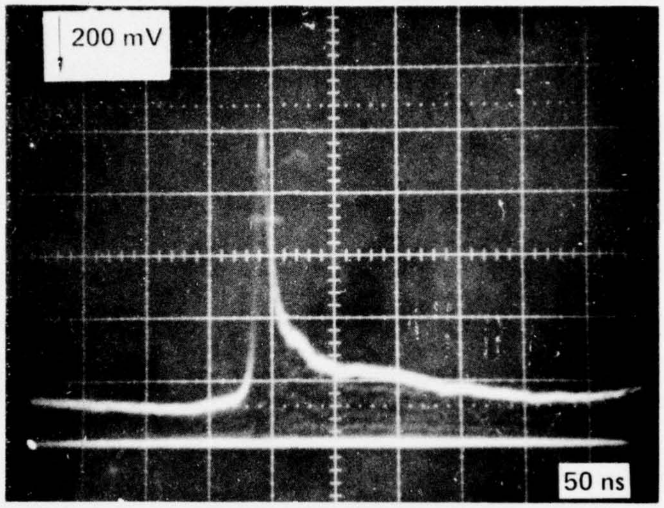
Several widely spaced spots were recorded on the photodichroic crystal with a recoding energy of 12.5 mj/cm^2. The signal was recovered with a single scan and observed on the oscilloscope. However, we were unable to record the single trace spot profile with photographic film. Figure 3-8a shows a photograph of the recovered spot profile with 32 overlapping scans on readout. Note the signal strength is several hundred millivolts.

A second series of widely spaced spots were recorded with an energy of 1.25 mj/cm^2. A recovery of the signal is shown in Figure 3.8b, where 320 overlapping scans were used to make the photograph. Note the signal strength is about 40 millivolts.

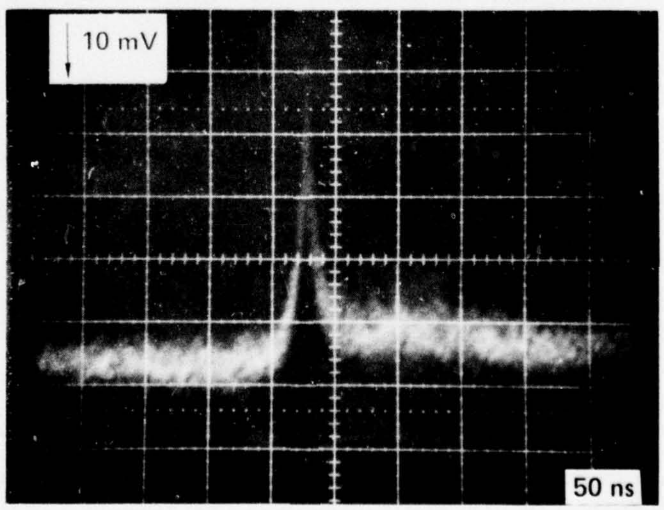
Assume that for an average signal to be recorded on the KF crystal, that 3 mj/cm^2 exposure is required. With this value, we can calculate the laser power required to record the subnano-second pulses at 100 MHz rate with a single scan. The laser power can be calculated from the following expression:

$$P_L = \frac{SA}{\eta T},$$

where P_L is the average laser power, S is the recording medium sensitivity, η is the system optical efficiency, T is the pixel exposure time, and A is the area of the focused spot. For a sample calculation of the laser power required, we use the following values:



a. READOUT WITH 32 SCANS
RECORDING ENERGY OF 12.5 mj/cm^2



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b. READOUT WITH 320 SCANS
RECORDING ENERGY OF 1.25 mj/cm^2

Figure 3-8. Signals Recovered With PMT

$$P_L = \frac{(3 \times 10^{-3}\ j/cm^2)\ (5 \times 10^{-4}\ cm)^2}{\eta\ (10^{-9}\ s)}$$

$$P_L = \frac{0.75\ W}{\eta}$$

The optical system efficiency, η, was reported in Paragraph 2.2 to be 2.4 percent; however, a comment was made that the optical efficiency could be improved by nearly an order of magnitude by antireflection coatings on all surfaces, and requiring that all lenses and surfaces have a transmission coefficient of at least 0.92. The exception to this would be the ATWL and the AOBD, which would have a transmission coefficient of 0.8, and 0.5 respectively. This would produce an overall optical efficiency of about 20 percent.

With a 20 percent efficient optical system, 3.75 watts of laser power at 514.5 nm would be required to record an average signal (3 mj/cm^2) on the KF crystal with a single scan. There are argon ion lasers on the market capable of producing approximately six to eight watts of laser illumination at this wavelength, so that a system using this technology could be made.

3.2.2 Decay Sensitivity

An experiment was performed to determine the decay of signal reconstructed from the photodichroic crystal as the crystal is read out. The experiment was performed with a readout beam wavelength of both 514.5 nm and 488 nm.

A series of widely spaced spots were recorded onto the photodichroic crystal at the 514.5 nm wavelength. The signal was recovered with the same waveiength using the PMT. The signal was recorded with an exposure of 14 mj/cm^2, while the readout exposure was about 66 μj/cm^2/scan. A 10 ms (320 scans) readout exposure was used to take a photograph of the recovered signal spot profile, producing a cumulative readout energy of approximately 2.1 mj/cm^2. A second photograph was taken of the recovered signal from the same recorded spots, where the total number of scans was 640 and the cumulative energy was 4.2 mj/cm^2. This was repeated until the signal could not be recovered using the PMT.

Figure 3-9 shows a graph of the PMT response versus the total number of scans used in the readout; across the top of the graph the cumulative readout energy is also given. Note that 14 mj/cm^2 was used to record the signals, with a cumulative readout energy of the same amount, the PMT has a response of about 40 mV, at the 514 nm wavelength.

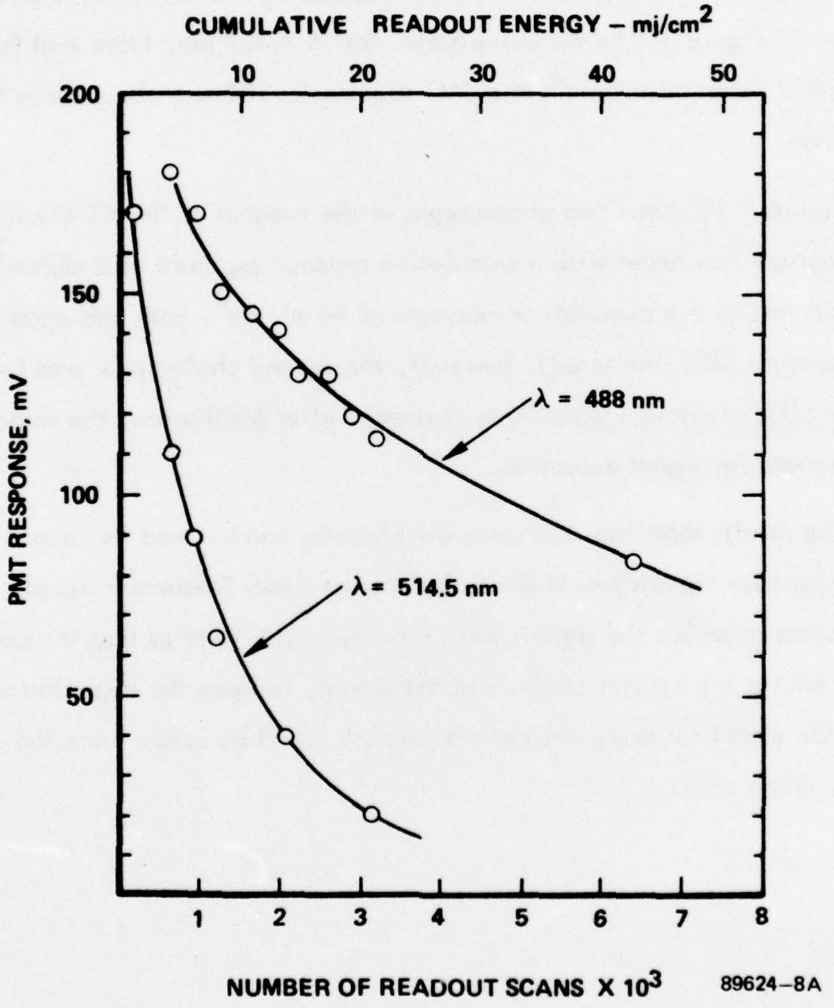
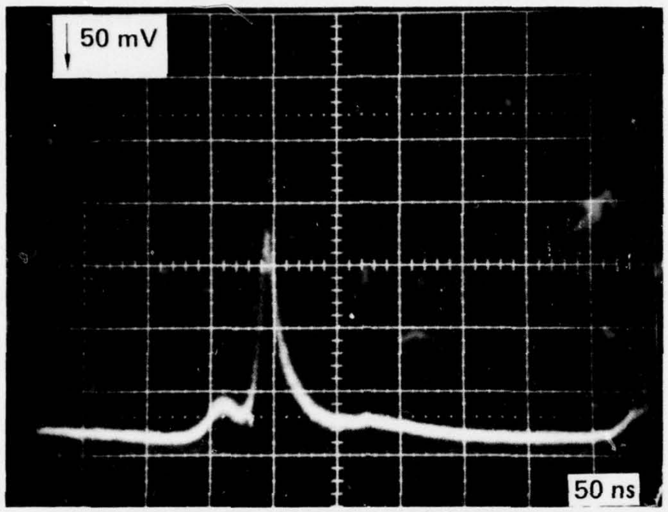


Figure 3-9. Decay Sensitivity of KF Crystal

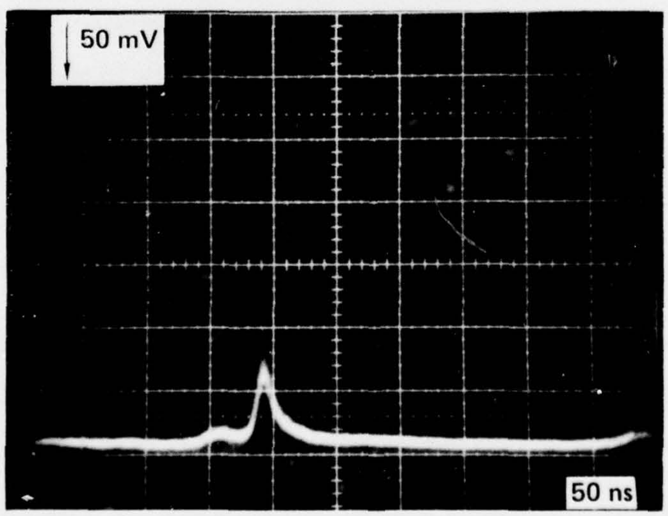
The experiment was repeated, with the exception that the readout of the laser illumination was changed to the 488 nm argon wavelength. The laser power was adjusted (taking into account the spectral response of the CRL 212b power meter) to provide the same exposure to the KF crystal on readout. Again a series of cumulative energy photographs were obtained of the oscilloscope trace. A measure of the PMT response was taken from the photographs. The results are shown in Figure 3-9 by the curve drawn for $\lambda = 488$ nm. Note that for a cumulative readout exposure of about 14 mj/cm^2, the PMT response is 130 mv; about three times greater than for $\lambda = 514.5$ nm.

Figure 3-10 shows two photographs of the readout of the KF crystal at $\lambda = 488$ nm. The upper photograph was taken with a cumulative readout exposure of 2 mj/cm^2, while the lower photograph was with a cumulative exposure of 44 mj/cm^2. Both photographs were taken with a 10 ms exposure (320 line scans), however, the second photograph was taken after the crystal had over 6000 previous scans. Note that even after 6000 scans, the response of the PMT is still adequate for signal detection.

The results show that the same wavelengths can be used for record/readout of the signals. High frequency signals would decay before the lower frequency signals, because of the depth of modulation at which the signals were recorded. This implies that it would be advantageous to use $\lambda = 488$ nm for the Fourier analysis of the signal, to keep the degradation of the signal to a minimum. On signal recovery, either wavelength could be used, since the data would be obtained with a single scan.



a. READOUT WITH 320 SCANS AT 488 nm
CUMULATIVE ENERGY – 2 mj/cm^2



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b. READOUT WITH 6.4K SCANS AT 488 nm
CUMULATIVE ENERGY – 44 mj/cm^2

Figure 3-10. Decay of Signal Reconstructed From KF Crystal

3.3 Dynamic Range Measurements

In this section we discuss the dynamic range measurements of the OTIS scanner using the photodichroic crystal. Measurements were made using the PMT signal recovery technique and by observing the spectrum of the recorded signal in the Fourier plane. Each of these measurement techniques will be discussed below.

3.3.1 Dynamic Range Measurement Using the PMT

The dynamic range of the OTIS scanner using the photodichroic crystal as a temporary optical signal buffer was made by recording widely spaced spots on the crystal at different exposure levels. The 3 MHz signals were then reconstructed by scanning with a laser beam of the same wavelength and detected with a PMT (56 UVP). The output from the photomultiplier tube was displayed on an oscilloscope and a photograph of the spot profile was made. The procedure was repeated for several other exposure levels on the photodichroic crystal.

A measure of the signal strength and the noise levels were obtained from the photographs at each exposure level. A signal-to-noise ratio was formed from this data, where the results are shown in Figure 3-11. Figure 3-11 shows a graph of the signal-to-noise ratio of the reconstructed signal versus the exposure used during the recording process. Note that the maximum signal-to-noise ratio occurs with an exposure of approximately 15 mj/cm^2; the minimum signal-to-noise ratio, detected using the PMT readout, occurred with an exposure of only 0.14 mj/cm^2. The PMT responded to longer exposure data; however, the signal-to-noise ratio of the reconstructed signals from the KF crystal continues to decrease at longer exposures, even though the signal strength continues to increase.

The dynamic range using this signal recovery technique was about 20 dB. However, this dynamic range measurement is limited by the polarizers, the sensitivity of the PMT, and the noise of the electronic amplifiers. The signal-to-noise ratios as shown in Figure 3-11 are pessimistic values, especially for the lower exposure levels. This was caused by the rapid decay of the signal intensity on readout, while the photograph was being taken on the oscilloscope. The SNR may be as much as 50 percent greater than the values shown in Figure 3-11 for the smaller exposure levels. Signals with smaller recording exposure levels can be detected with the OTIS scanner; photographs of the oscilloscope trace were not possible with the equipment that we were using. Therefore, the

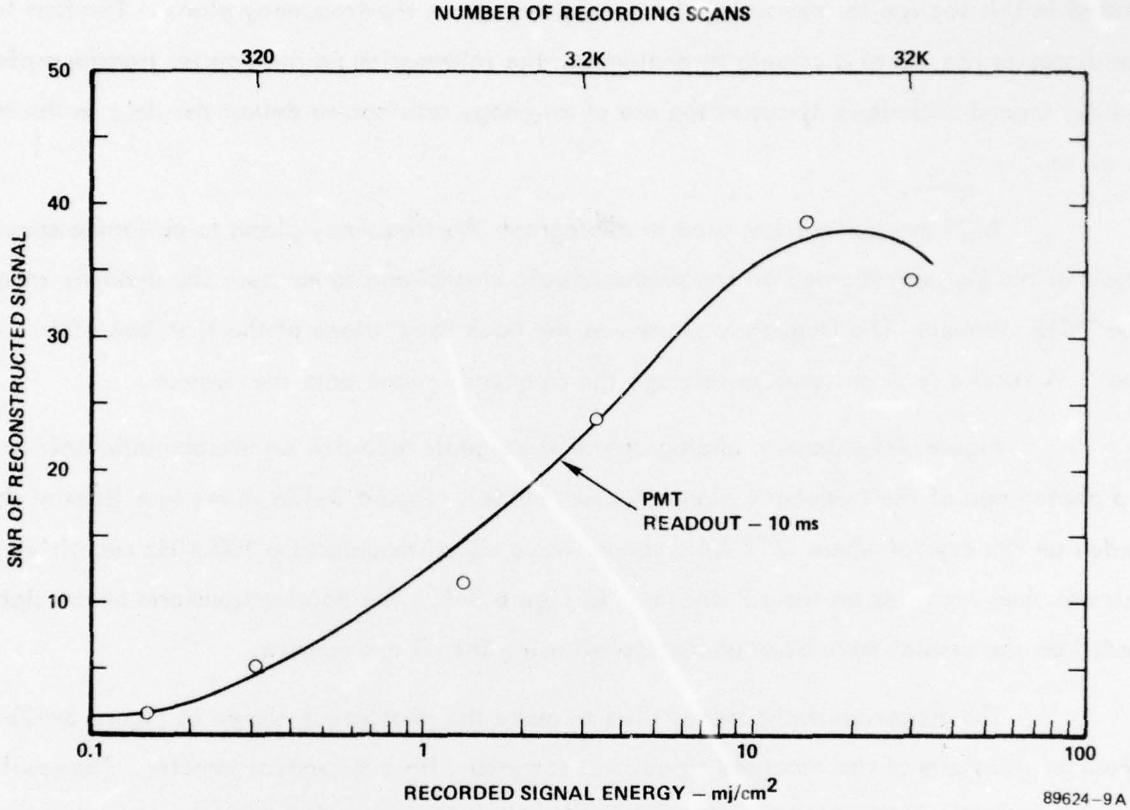


Figure 3-11. Dynamic Range Measured Using a PMT

dynamic range of the signals recorded and recovered on the KF crystal is greater than the reported 20 dB.

3.3.2 Dynamic Range Measurement in the Fourier Plane

A measure of the dynamic range of the OTIS scanner using the photodichroic crystal was made by detecting the spacial frequency in the Fourier transform plane of the recorded signal. By recording several scan lines of signal data at the same frequency, the reconstructed signal from these lines is coherently added in the Fourier transform plane to produce a bright image point that corresponds to the spatial frequency of the signal that was recorded on the crystal. This provides a very sensitive means for measuring the dynamic range of the system. Two techniques are

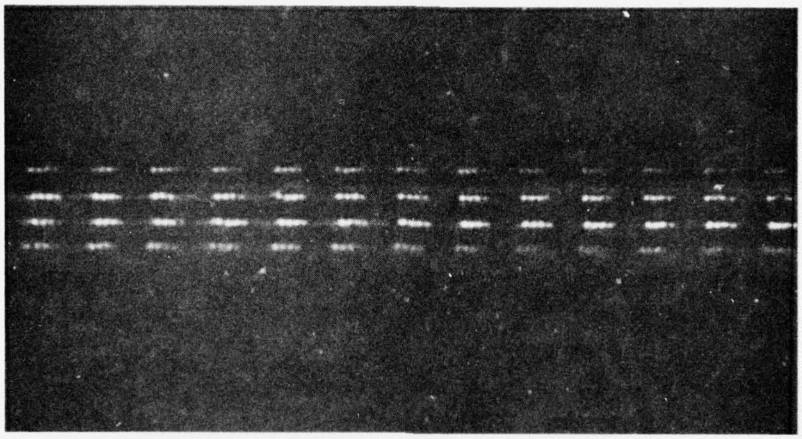
discussed in this section for measuring the dynamic range in the frequency plane. The first technique discusses the use of a camera to photograph the information in the Fourier transform plane, while the second technique discusses the use of an image orthicon to detect the data in the transform plane.

A 35 mm camera was used to photograph the frequency plane to perform a spectrum analysis of the signals recorded on the photodichroic crystal and to measure the dynamic range of the OTIS scanner. The frequency plane was the back focal plane of the first lens after the KF crystal. A second lens was used to reimage the frequency plane onto the camera.

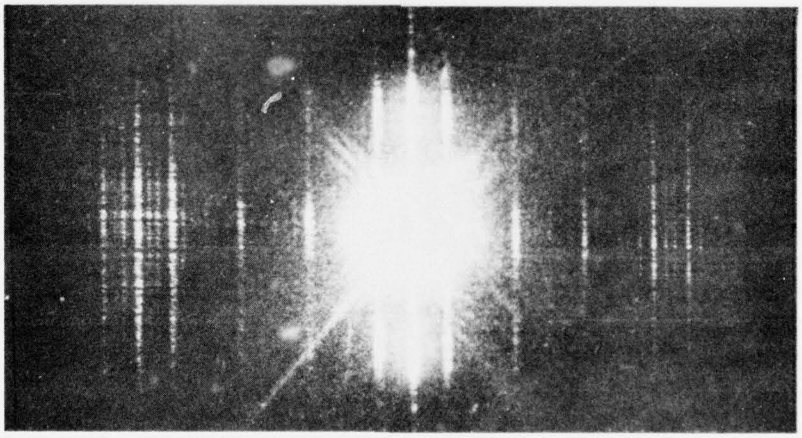
Figure 3-12 shows a photograph of the signals recorded on the photodichroic crystal and a photograph of the frequency plane (Fourier Plane). Figure 3-12a shows four lines of data recorded on the crystal where a 12 MHz square-wave signal modulates a 100 MHz repetitive signal which was then recorded on the KF crystal. In Figure 3-12b the Fourier transform of the signals recorded on the crystal have been photographed using the 35 mm camera.

The negative transparency used to make the photograph shown in Figure 3-12b of the Fourier transform of the recorded signal was scanned with a microdensitometer. The results of this scan are shown in Figure 3-13 where a density trace is shown of the frequency spectrum of the signals recorded on the KF crystal. Note that the 12 MHz square wave and its odd harmonics occur at 12, 36, 60, 84 MHz. The 96.6 MHz mode-locked frequency from the laser is shown along with a beat frequency of 4.5 MHz. The ±4.5 MHz beat frequency can be seen on either side of the mode-locked frequency and on either side of the seventh harmonic, of the 12 MHz square wave. At first, it was not clear where this frequency came from because it was not intentionally recorded on the crystal. However, we found that the external modulator and the mode-locked laser were not phase locked, and there was a 4.5 MHz beat frequency between the two.

The Gaussian weighted illumination on the KF crystal caused the reconstructed signals to have an amplitude modulation. Whenever amplitude modulation (am) and frequency modulation (fm from the ±4.5 MHz beat frequency) are present, the spectrum has unequal side lobes. Note that the peak intensity of the signals displayed on one side of the spectrum are not equal to those on the other side.



a) DATA RECORDED ON PHOTODICHROIC CRYSTAL



b) FOURIER TRANSFORM OF RECORDED DATA

Figure 3-12. Photographs of the Signals Recorded and Their Fourier Transform

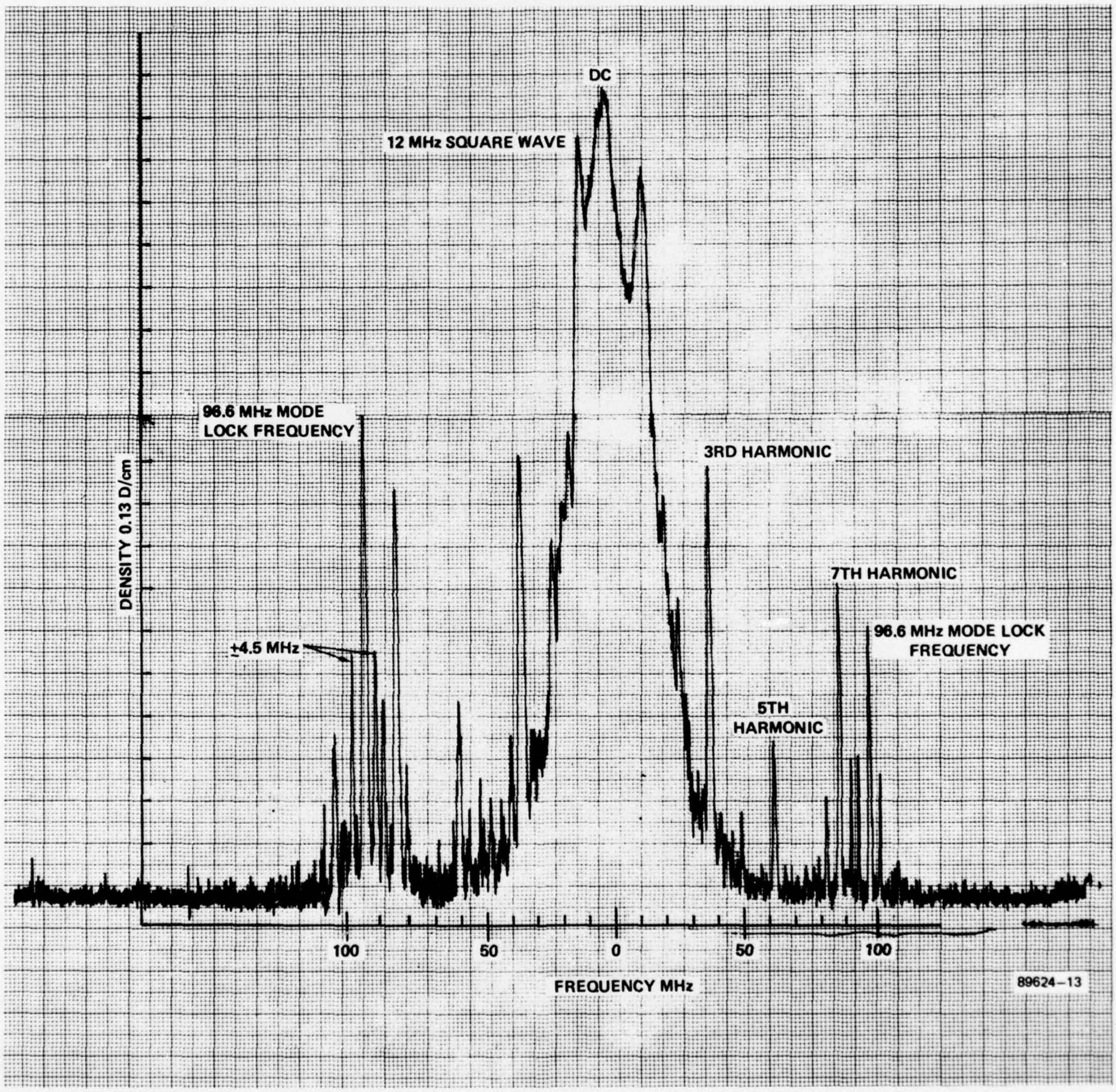


Figure 3-13. Microdensitometer Sc n of the Film Showing the Fourier Transform of the Signal

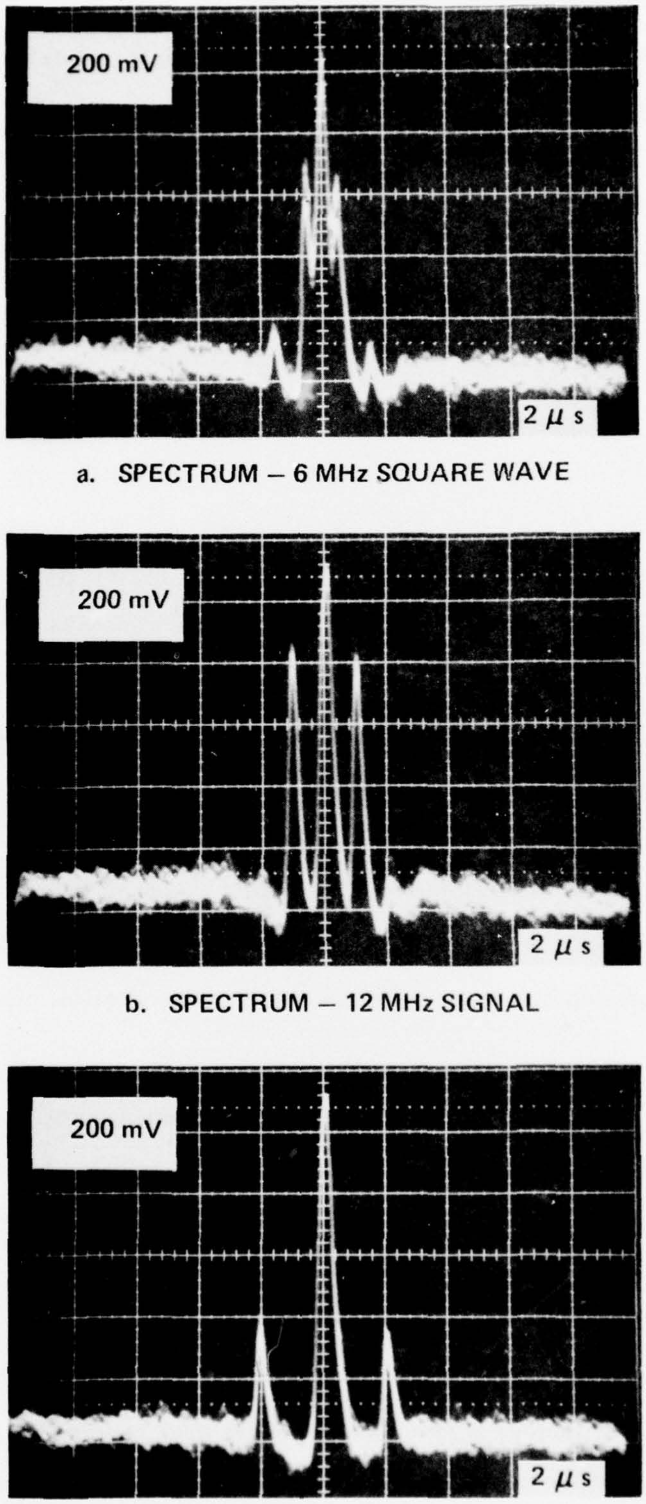
We found that this approach was not very useful for measuring the dynamic range of the system for several reasons. First, for small signal amplitudes recorded on the KF crystal, the signals would decay before an adequate photograph could be obtained using the 35 mm camera focused on the transformed plane. Secondly, it was difficult to accurately scan the transparencies of the Fourier Plane with a microdensitometer because of the small size of the images formed. Thirdly, the nonlinear recording effects of the 35 mm photographic film, were difficult to account for, in determining the dynamic range of photodichroic crystal.

In the second technique for measuring the dynamic range in the Fourier transformed plane, the 35 mm camera was replaced with an image orthicon. The image orthicon displays an image of the Fourier Plane on a TV monitor. The TV system has a line selector, which allows any video line to be selected and displayed on an oscilloscope. By selecting the proper line, the oscilloscope trace displays an intensity profile of the Fourier transform of the signals recorded on the KF crystal.

An experiment was performed where the crystal was used to record 100 vertically spaced scan lines all at the same exposure level. On readout, a collimated laser beam is used to illuminate the crystal, and the first lens is used to perform the Fourier transform. The Fourier transform plane is imaged onto the orthicon (TV camera). Various frequencies and exposure levels were recorded on the crystal; the spectrum was detected with the orthicon, and displayed on the oscilloscope. Several photographs were taken of the intensity profiles displayed on the oscilloscope.

Figure 3-14 shows three photographs of the intensity profile of the Fourier transform plane for three different signal frequencies stored on the KF crystal. The spectrum of a 6 MHz square wave, 12 MHz, and 25 MHz sine wave are shown respectively. Note that the third order harmonic of the 6 MHz square wave is shown in the first photograph. Figure 3-15 shows two photographs of the intensity profile of the spectrum for 50 MHz, and 96.6 MHz signals recorded on the KF crystal.

Using this technique, where 100 scan lines were recorded and simultaneously illuminated to form the spectrum, recording exposures ranged from 1 ms to 2 seconds. This corresponds to 28 $\mu j/cm^2$ (32 scans) up to 60 mj/cm^2. The dynamic range using this technique was 33 dB.



a. SPECTRUM – 6 MHz SQUARE WAVE

b. SPECTRUM – 12 MHz SIGNAL

c. SPECTRUM – 25 MHz SIGNAL

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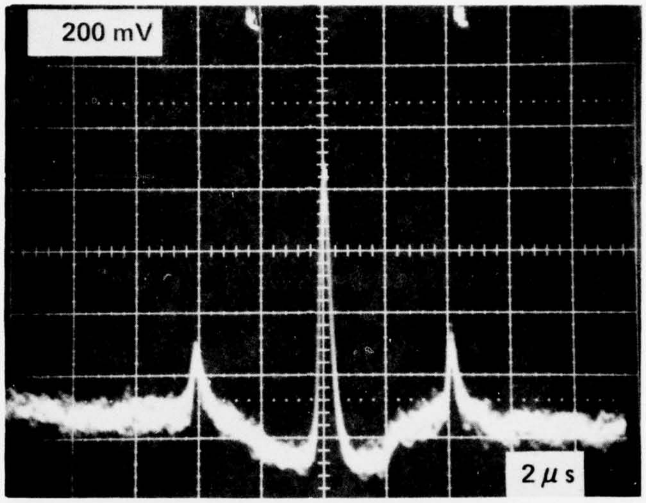
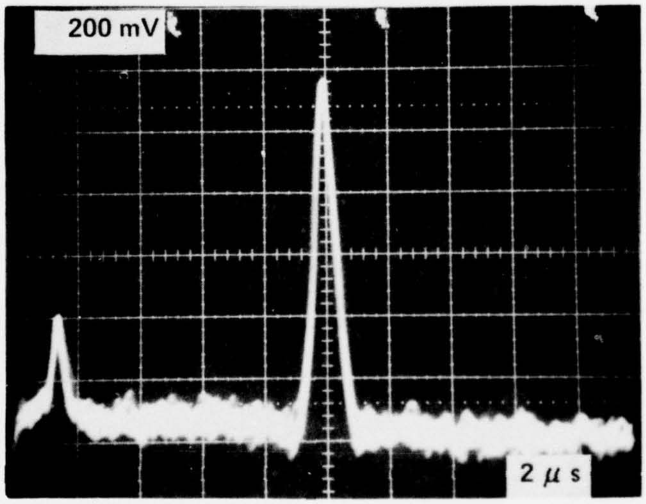
Figure 3-14. Three Photographs Showing the Spectrum of the Recorded Signal, Detected by a Image Orthicon TV Camera



a. SPECTRUM – 50 MHz SIGNAL



b. SPECTRUM – 96.6 MHz MODE LOCK FREQUENCY

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Figure 3-15. Two Photographs Showing the Spectrum, of the Recorded Signal, Recovered With a TV Camera

SECTION 4.0

CONCLUSION AND RECOMMENDATIONS

4.0 CONCLUSION AND RECOMMENDATIONS

Our conclusion based on this study was that a carefully designed acousto-optic laser scanner system would be required, where the optical efficiency was at least 20 percent to use this technology for OTIS. The system would require at least 3.75 watts of laser power to record onto the photodichroic crystal. On readout, if the same scanning spot size was used to recover the signal as the spot size used to record the signal, then a 3-dB decrease in the MTF of the recovered signal can be expected. The dynamic range, appeared to be limited by the equipment used (PNT, polarizers, etc.) and not by the dynamic range of the KF crystal.

Our recommendations for future study using this technology to solve the OTIS problem include the following:

- Continue to develop and improve the KF crystal
- Trade off analysis of y-scan alternatives
- Implement a Y-scan to the laser scanner
- Develop a wideband AO modulator
- Record Real-Time Signal in a Raster Format-study spectrum characteristics
- Study signal recovery techniques
- Conceptual system design
    - Laser
    - ATWL and drive
    - AOBD and drive
    - Optics
    - Record mode
    - Modulator
    - Readout mode